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Total number of authors:
20

Published in:
Proceedings of UCMMT2012

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

Citation (APA):

Paoloni, C., Di Carlo, A., Brunetti, F., Mineo, M., Ulisse, G., Durand, A., Krozer, V., Kotiranta, M., de Rossi, A., Dolfi, D., Legagneux, P., Fiorello, A. M., Dispenza, M., Secchi, A., Zhurbenko, V., Megtert, S., Bouamrane, F., Bouvet, T., Cojocaru, C-S., & Gohier, A. (2012). A European Project on Vacuum Tube Amplifiers for THz Amplification. In *Proceedings of UCMMT2012*

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A European Project on Vacuum Tube Amplifiers for THz Amplification

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Abstract- The OPTHER (Optically Driven THz amplifier) project supported by the European Commission within the Seventh Framework Program (FP7) represents the first joint European attempt to realize vacuum electron devices in THz range. The target of the project was to design and realize the first 1 THz vacuum tube amplifier. The challenges of the presented task and the innovative solutions adopted established a new level of knowledge in the field. The main aspects of the OPTHER project are described, focusing on challenges and adopted innovative solutions.

I. INTRODUCTION

The progress of THz technology depends on performance and availability of THz components [1] [2]. In particular, THz sources have to meet a series of tight specifications: sufficient output power, reliability, room temperature operation, compact size, light weight, portability, and low cost. The combination of these tough requirements forms the challenge to fill the so-called THz-gap. A great number of research groups worldwide is attempting to fill the THz-gap by exploiting solid-state technologies, optoelectronic and vacuum electronics [2].

Contrary to solid state devices, that are limited in output power, and optoelectronic approaches (e.g. Quantum cascade laser), that require a cryogenic cooling, vacuum electron sources seems to be a promising solution allowing an output power level suitable for many THz applications. Presently, the advances in microfabrication processes allow the realization of micro vacuum electron devices with dimensions suitable for THz frequency range [3] [4] [5] [6].

The OPTHER project, supported by the European Commission, aims to design and construct the first vacuum tube amplifier at 1 THz [7].

A consortium of academic and industrial partners was gathered for this purpose.

In this paper, the main challenges and the outcomes of the OPTHER project are described.

II. OPTHER PROJECT

The specifications of the vacuum tube amplifier in the OPTHER project are listed in Table I.

TABLE I
OPTHER SPECIFICATIONS

Requirement	Specification
Operating frequency	1 THz
Output power	10 mW
Gain	10 dB
Beam voltage	10 kV
Bandwidth about	~1%
Environmental conditions	room temperature
Cost	< 20000 €
Weight	~1 Kg
Volume	< 1 dm ³

The operating frequency is about five times the highest frequency of any vacuum amplifier ever reported [4] [8] [9]. It is easy to understand that there were neither experience, experimental results, nor tool proved reliable at these frequencies. The first obstacle that the consortium had to face

was to create knowledge for THz amplification. The two following requirements highly increase the level of difficulty in the project. The first requirement was to set the beam voltage at 10 kV to reduce the dimensions and the power supply requirements, for portability. The second one was the use of a cylindrical beam. Both these specifications had a big impact on the design approach. Further the overall dimensions and weight have to be fully compatible with portability as well.

The use of a corrugated waveguide was mandatory from the point of view of the fabrication aspects [10]. The period of the corrugation is highly related to the operating frequency and the beam voltage. The forward wave regime, typical for TWTs was unfeasible because the associated period is too short to be realized using available technology. The backward wave regime, where the synchronism is with the first negative harmonic allows a longer period, which is within the range of the available fabrication technology [9] [12]. First, the chosen topology was a backward wave amplifier [11] and then a more complex cascade backward wave amplifier [13] was found more effective. A gain of about 14 dB was simulated.

The different aspects of the design and realization will be outlined in the following.

A. Cathode and Electron gun

Two novel approaches were considered: the optically modulated electron beam [14] and the carbon nanotube cold cathode [15].

The optically modulated electron beam was an extremely advanced solution. The optical control is based on a nanostructured metallic surface which is able to convert an incident optical beam with wavelength within a suitable span (specifically the telecom band 1500nm ~ 1600nm) into a localized surface wave such that the electric field is oriented perpendicular to the surface and is enhanced. That would ensure maximal interaction with carbon nanotubes, thereby enabling fast modulation of the emission of the CNT cold cathode by an optical control (Fig.1). The extreme advanced nature of the approach requires however further investigation to generate an adequate beam modulation.

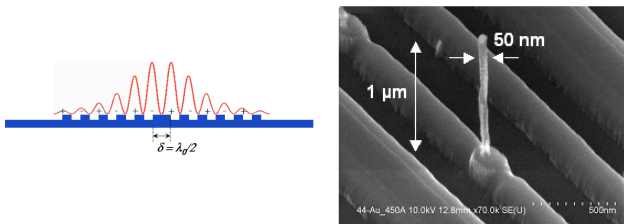


Figure 1. Optically modulated cathode.

A relevant investigation was performed, and is still in progress, to realize a carbon nanotube (CNT) cold cathode. Different patterns of CNT emitting structures were investigated and realized by the CVD technique. The

transverse electron velocity represents a key issue for the correct generation of the electron beam and a suitable cathode structure was designed. Fig.2 shows the effect of the transverse velocity compensation on the beam shape [15]. The external grid cold cathode is shown in Fig.3.

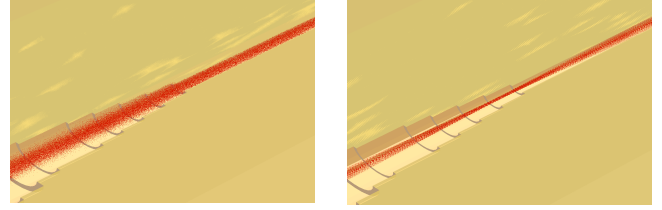


Figure 2. Transverse electron velocity effect: a) without compensation; b) compensated.

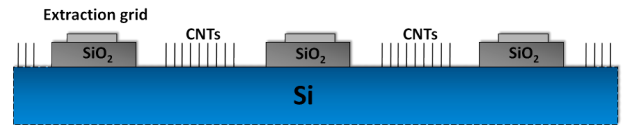


Figure 3. CNT integrated grid cold cathode.

The cold cathode approach requires further investigation to be used in THz tube. To test the tube, a thermionic electron gun was designed and realized.

B. Slow wave structure

The available high aspect ratio fabrication processes (Direct Ion Etching (DRIE), UV-LIGA SU-8 photolithography and X-ray LIGA (German acronym for lithography, electroplating, and molding) due to their properties, limit the degrees of freedom of the structure shape to two dimensions. The consequence is that these techniques are suitable for realizing structures supporting a sheet electron beam. Since the sheet beam technology is not so mature, it was decided to adopt a cylindrical beam. This posed a great challenge that was overcome by the double corrugated waveguide [16] (Fig.4). This slow wave structure supports a cylindrical beam and can be realized by photolithographic technique.

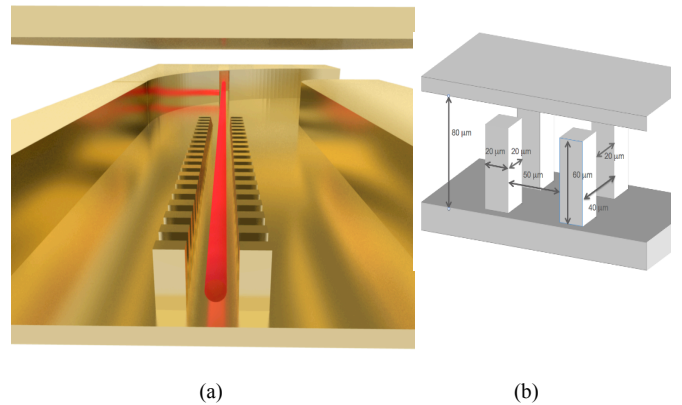


Figure 4. Double corrugated waveguide: a) rendering; b) dimensions.

C. Input and output coupling

The feeding of the RF signal at 1 THz was a critical issue due to the high level of losses [17] and to the lack of reliable measured values. A vertical tapering of the double corrugated waveguide (Fig.5a), provided the best input/output coupling performance, but the number of steps required for its realization made this unfeasible [18]. The solution was to taper the lateral position of the corrugations (Fig.5b). This approach also guaranteed a good coupling and compatibility with the technological process. The simulated S-parameters of the coupling structure are shown in Fig. 5.

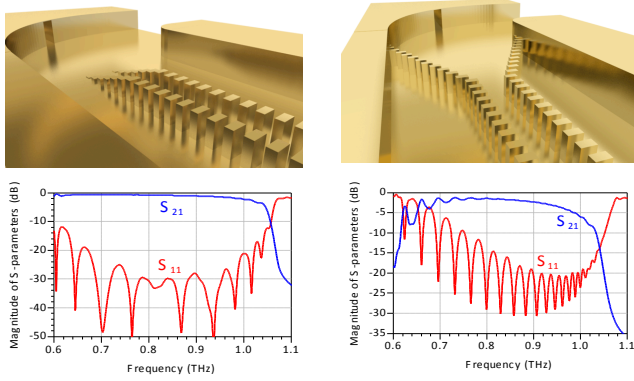


Figure 5. a) vertical taper; b) lateral taper

D. Photolithographic fabrication

The dimensions of the parts of the designed double corrugated waveguide operating in backward wave mode at 1 THz are in the range of dozens of microns. Two fabrication techniques were used: SU-8 UV-LIGA and X-ray LIGA. The results obtained by SU-8 UV-LIGA (Fig. 6) were promising, but the X-ray LIGA was more reliable and accurate. X-ray LIGA is based on illuminating the mask by the synchrotron light. Different steps were performed to get the best result. Firstly the mask accuracy was tested on PMMA (poly (methyl methacrylate)), (Fig.7). Some steps of copper electrogrowth were performed to get the adequate surface finishing of the metal wall and the precision of the dimensions (Fig. 8 and Fig. 9). Finally, the whole structure, including the input and output coupler was realized (Fig.10). Some imperfections in the SWS prevented to have measurements of the devices, so a second assembly run is necessary.

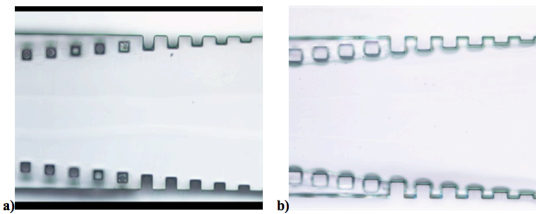


Figure 6. SU-8 UV LIGA fabrication

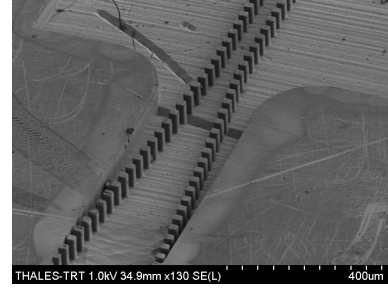


Figure 7. PMMA fabrication to test the mask

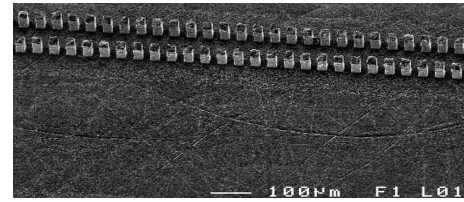


Figure 8. First copper electrogrowth

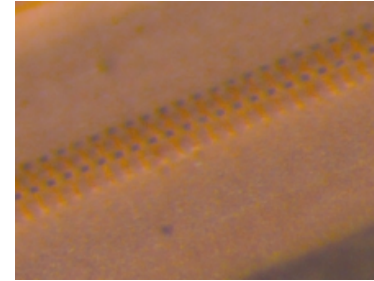


Figure 9. Improved copper electrogrowth

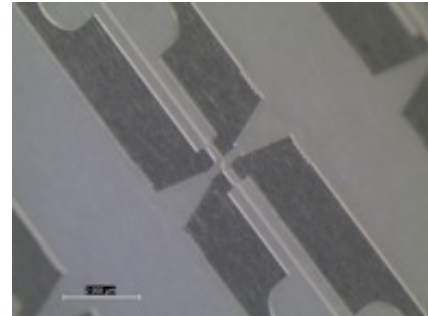


Figure 10. Complete SWS realization

E. Assembling

The assembling of the tube represented a challenging phase due to the dimensions of the parts and alignment issue. A drawing of the vacuum envelope is shown in Fig. 11.

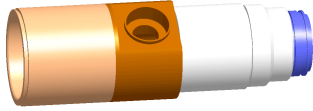


Figure 11. Drawing of the vacuum envelope

III. CONCLUSION

The first ever designed and realized 1 THz cascade backward wave amplifier is presented. Due to the lack of experience and knowledge for amplification at THz frequencies, a huge theoretical and experimental effort due to the lack of experience and knowledge for amplification at THz frequencies was required from the Consortium.

ACKNOWLEDGMENT

This work was supported by the FP-7 European Project n.224356 "OPTHER- Optically Driven THz Amplifiers".

REFERENCES

- [1] J. F. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, and D. Zimdars, "THz imaging and sensing for security applications - explosives, weapons and drugs," *Semiconductor Science and Technology*, vol. 20, no. 7, pp. 266–280, 2005.
- [2] P.H.Siegel, "Terahertz Technology," *IEEE Trans. on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 910–928, March 2002.
- [3] R. L. Ives, "Microfabrication of High-Frequency Vacuum Electron Devices," *IEEE Trans. On Plasma Science*, Vol. 32, No. 3, pp.1277-1291, June 2004.
- [4] Y. M. Shin, J. K. So, S. T. Han, K. H. Jang, G. S. Park, J. -Hyun Kim and Suk-Sang Chang, "Microfabrication of millimeter wave vacuum electron devices by two-step deep-etch x-ray lithography," *Appl. Phys. Lett.* 88, 091916 (2006).
- [5] J. Tucek, D. Gallagher, K. Kreischer, and R. Mihailovich, "A compact, high power, 0.65 THz source," *IEEE International Vacuum Electronics Conference Proceedings, (IVEC 2008)*, pp. 16-17, Apr. 22 – 24, 2008.
- [6] M. Mineo, C. Paoloni, "Corrugated Rectangular Waveguide Tunable Backward Wave Oscillator for Terahertz Applications," *IEEE Trans. on Electron Devices*, vol.57, no.6, pp.1481-1484, June 2010.
- [7] OPTHER Project website: www.opther.eu.
- [8] J. C. Tucek, M. A. Basten, D. A. Gallagher, and K. E. Kreischer, "220 GHz Power Amplifier Development at Northrop Grumman," in *Proc. IEEE IVEC/IVESC*, pp. 553–554, April 24–26, 2012.
- [9] Y. M. Shin, L. R. Barnett, and N. C. Luhmann, Jr., "Phase-Shifted Traveling-Wave-Tube Circuit for Ultrawideband High-Power Submillimeter-Wave Generation," *IEEE Trans. on Electron Devices*, vol.56, no.5, pp.706–712, May 2009.
- [10] M. Mineo, A. Di Carlo, and C. Paoloni, "Analytical design method for corrugated rectangular waveguide SWS THz vacuum tubes," *Journal of Electromagnetic Waves and Applications*, Vol. 24, Nos. 17–18, pp. 2479–2494, 2010.
- [11] C. Paoloni, A. Di Carlo, F. Brunetti, M. Mineo, G. Ulisse, A. Durand, V. Krozer, M. Kotiranta, A. M. Fiorello, M. Dispenza, A. Secchi, V. Zhurbenko, F. Bouamrane, T. Bouvet, S. Megtert, E. Tamburri, C.-S. Cojocar, A. Gohier, "Design and Fabrication of a 1 THz Backward Wave Amplifier", *International Journal Terahertz Science and Technology*, vol.4, n.4, pp. 149-162, Dec. 2011.
- [12] R. Kompfner and N. T. Williams, "Backward Wave Tubes," *Proceedings of the IRE*, vol.41, no.11, pp.1602– 16011, Nov. 1953.
- [13] M. R. Currie and J.R. Whinnery, "The Cascade Backward-Wave Amplifier: A High-Gain Voltage-Tuned Filter for Microwaves", *Proc. OfIRE*, pp. 1617-1631, November 1955.
- [14] P. Legagneux, N. Le Sech, P. Guiset, L. Gangloff, C. Cojocar, J. P. Schnell, D. Pribat, K. B. K. Teo, J. Robertson, W. I. Milne, F. Andre, Y. Rozier, D. Dieumegard, "Carbon nanotube based cathodes for microwave amplifiers," *IEEE International Vacuum Electronics Conference Proceedings, (IVEC 2009)* , pp. 80–81, April 28–30, 2009.
- [15] Ulisse, F. Brunetti, A. Di Carlo, "Study of the Influence of Transverse Velocity on the Design of Cold Cathode-Based Electron Guns for Terahertz Devices", *IEEE Trans. on Electron Devices*, vol. 58, no. 9, pp. 3002 – 3004, Sept. 2011.
- [16] M. Mineo, C. Paoloni, "Double-Corrugated Rectangular Waveguide Slow-Wave Structure for Terahertz Vacuum Devices," *IEEE Trans. on Electron Devices*, vol.57, no.11, pp. 3169–3175.
- [17] S. Lucyszyn and Y. Zhou, "Engineering Approach to Modelling Metal THz Structures," *Terahertz Science and Technology*, Vol.4, No.1, March 2011.
- [18] V. Zhurbenko et al., "Excitation of a Double Corrugation Slow-wave Structure in Terahertz Range," *Proceedings of the 5th European Conference on Antennas and Propagation, EuCAP 2011*, pp. 1092-1094.